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SOURCE K. E. Tsiolkovskiy, Works on Rocket Techniques, published by Oborongiz, 1947. (FDB 475392).

WORKS ON ROCKET TECHNIQUES

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[This publication contains the table of contents, introduction, and extracts from the section on fuels from Works on Rocket Techniques, a compilation of works by Tsiolkovskiy, founder of Russian rocket science. The book is largely historical, contains little data with practical application, and scientifically is poor by present standards.]

TABLE OF CONTENTS

	Page
Rockets in Cosmic Space (1903)	25
Altitudes attained in free balloon flights; dimensions and weight of balloons	25
Temperature and density of the atmosphere	25
Rockets and cannons	28
Advantages of using rockets	31
Rockets in a medium free of gravity or atmosphere. Relationship of the mass of the rocket.	32
Speed of flight in relation to fuel consumption	38
Efficiency of the rocket for gaining altitude	39
Rockets Under the Influence of Gravity	41
Vertical climb	41
Determination of attainable altitude	41
Efficiency	46
Gravitational fields. Perpendicular return to the earth	48
Gravitational fields. Climb at an incline	51
Climb at an incline. Power expended in climb as opposed to power expended in climb in a medium not possessing gravitational force. Work losses.	53

- 1 -

CLASSIFICATION

~~SECRET~~

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SECRET

50X1-HUM

	<u>Page</u>
The Use of Rocket-Powered Equipment to Study the Universe (1911)	58
Resume of work done in 1913	58
The effect of gravity when departing from planets	61
Speeds necessary to overcome the gravitational pull of planets	62
Duration of flight	62
Atmospheric resistance	63
The general flight picture	68
Graphs showing the movement and speed relation of rockets	73
Essential factors for flight	80
Nutrition and respiration	80
Methods of overcoming extreme gravitational pull	84
Allowances for lack of gravity	87
Future jet-powered equipment	89
The Use of Rocket-Powered Equipment to Study the Universe (1914)	93
The Use of Rocket-Powered Equipment to Study the Universe (1926)	103
The airship must be adapted to the rocket	105
Basic data necessary for complete study of this problem	106
The effect of gravity when departing a planet	106
Necessary speeds	108
Duration of flight	109
The effect of solar gravitation	110
Atmospheric resistance to a moving projectile	111
Available energy	112
Achievement of general cosmic speeds	114
The action of rockets	119
Efficiency of a rocket	119
Speed of a rocket by utilizing outside forces	121
Conversion of thermal energy into mechanical movement	124
Motion of a rocket produced by thrust, in a vacuum and a medium free from gravity	127
Determination of the speed of rockets	128
Duration thrust	130
Mechanical efficiency	131
Movement of a rocket in a vacuum, when gravity is present	134
Determination of the resulting acceleration	134
Work and waste of a rocket; mechanical efficiency	135
Flight of a rocket through the atmosphere, when gravity is present	137
More accurate methods for calculating atmospheric resistance	140
The most efficient angle of flight	143
Climb, landing on another planet and return to earth	149
Horizontal movement of an inclined projectile in a homogeneous atmosphere	151
Horizontal movement of a projectile, which is not inclined in a homogeneous atmosphere	153
Climb into the atmosphere from the take-off angle	156
Power Plant and Fuel Expenditure	158
Terrestrial rocket	160
Shape of a terrestrial rocket	169

- 2 -

SECRET

SECRET
SECRET

50X1-HUM

	<u>Page</u>
Cosmic Rocket (Space Ship)	169
Materials supplying the thrust	172
Detailed description of the rocket	174
Plans for Conquering Interplanetary space	178
Space Ship (1924)	188
Space Ship. Test Preparations (1927)	199
Space Trains (1929) [Wac Corporal in many sections]	215
What is a space train?	216
Construction and operation of space trains	217
Determination of the speed and other characteristics of space trains	219
Independent systems of space trains	237
Temperature factor in space ships	240
Jet Engines (1929)	244
New Airplanes (1929)	246
Determination of flight speed and other characteristics	248
Airplane types adaptable for all flight speeds	260
Jet-Powered Airplane (1930)	262
Jet-Powered Airplane ("Raketoplan")	272
Auxiliary Jet-Powered Stratoplane ("Stratoplan polyreaktivny")	287
Brief description	287
Air compressor	291
Computations on the compressor	292
The air screw	295
Acceleration of the stratoplane	298
Density of the atmosphere	299
Work of the air screw	299
Exhaust reaction of engines	301
Elongation of the fuselage	303
Wing thickness	303
Shape of the projectile. Rudders	304
Dimensions, area, surface and displacement	305
Fuel reserve limits for the engine	306
Ultrahigh pressures and the thickness of the stratoplane covering fabric	308
Jet-Powered Travel (1932)	313
Rocket Fuel (1933 to 1934)	324
Explosion and the engine	325
Selection of the combustible elements	327
Gas and Steam Turbine Engines (1933 to 1934)	332
Projectiles Attaining Space Speeds in the Earth's Atmosphere and in Water (1933)	340

- 3 -

SECRET
SECRET

SECRET

50X1-HUM

	<u>Page</u>
Maximum Speed of Rockets (1935)	348
Relationship between the speed of rockets and the thrust	348
Speed of the rocket when there is incomplete fuel combustion	348
Speed attainable by a rocket with the aid of auxiliary motive power	353
Desirable development trends	355
The goal of new developments	357
Exhaust speed of combustion products	358

Appendix

Comments on K. E. Tsiolkovskiy's "Selected Works," by F. A. Tsander	361
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INTRODUCTION

Tsiolkovskiy began work on rockets after reading a book by A. P. Fedorov, "New Principles of Air Navigation." Certain parts from an article written by Tsiolkovskiy in 1883 show that he was aware even then of the principles of rockets.

Tsiolkovskiy also wrote about air navigation, astrophysics, geology, and geochemistry. He was not recognized by the rulers of Czarist Russia, even though such eminent scholars as Mendeleev and Stoletov tried to attract the people to his ideas. At present, however, "leading Soviet scholars and engineers value Tsiolkovskiy's work highly." In the 1920's many foreign scientists took an interest in his work, among them Obert and Lademan.

Although his suggestion concerning placing rudders in the gas jet from the rocket motor tube, and thus enabling the guiding of the rocket in space or in the upper layers of the atmosphere met with opposition from Lademan, it is interesting to note that the same principle was used in the German V-2. Tsiolkovskiy described a rocket which would use liquid oxygen as an oxidizer, a rocket in which the fuel is fed to the combustion chamber by pumps, and a rocket which would be automatically controlled. All of these ideas were used in the V-2.

A list of the articles not published in the book is included.

M. K. Tikhonravov
Moscow, 1946

ROCKET FUEL

There is no essential difference between combustion and explosion. Earlier findings (1895) reveal that the required power of a motor for a constant motor weight is proportional to the speed.

Explosion and the Engine

Combustion-explosion takes place continuously in any combustion chamber, especially where jets are used. However, this explosion is not used directly as in the usual steam engine or turbine. Only the heat obtained is used. When using cheap fuel such as peat or coal and not restricted by the weight of the engine, great economy is attainable. But in a locomotive the fuel is purer and more expensive, the economy less. Witness the attempt to change to combustion engines (gasoline and Diesel) or to electric.

- 4 -

SECRET

SECRET

50X1-HUM

In the second case, we have internal combustion engines. Here the force of explosion is used and therefore these motors should be called explosive. They have the advantage of enormous energy, economical utilization of fuel, and therefore small stores of fuel. Their disadvantages are that the fuels are purer and more expensive. In both cases, no oxygen from the air is used.

Reactive automobiles, seaplanes, sledges, airplanes, stratoplanes or spaceships use previously stored oxygen or another element necessary for combustion. The purpose is to obtain enormous energy in a short time. We have two methods available here.

1. The oxygen element or the substitute for it may be previously mixed with the combustible part (powder, for example). Up to now, only prepared explosive materials have been used for movement or flight.

The advantages of this method are the arbitrarily rapid release of energy and simplicity in the construction of the motor. The disadvantages are many more, and are the danger of a general explosion of the entire store, burden of carrying the weight of the oxygen compound or liquid oxygen, burden of the weight of the tubes which carry the explosive material and which must withstand the enormous pressure of the exploding compressed combustion products (due to this, the tubes must be strong and heavy). At the low speeds attainable in the lower layers of the atmosphere, the small percent of utilization of the chemical energy makes the explosive substances very expensive.

2. The oxygen compound is separated from the fuel. The elements are combined gradually, as in an aircraft motor, except that the oxygen is not taken directly from the air. There is no danger of a general explosion. The burden of the heavy tubes does not exist, but other disadvantages remain.

What forces us to resort to stored oxygen? At very high altitudes, in exceedingly rarefied air or even higher, in space, a store of any oxygen compound is absolutely necessary because it is practically impossible to draw oxygen out of the atmosphere and it is utterly impossible in outer space.

We can attain great speeds here and the utilization of chemical energy may be very high. Disadvantages are the burden of the weight of the hydrogen and high cost. But the following may serve as elements of explosion: cheap oil (fuel) and liquid oxygen or its compounds, for example, liquid nitrogen peroxide. These are not so expensive. Separation of the elements of explosion is already being accomplished in small flying devices (without people). Obviously, progress is being made; but these devices have another disadvantage, which I pointed out in the periodical "Samolet" (Airplane) (1932). Therefore, even they yield poor results.

Selection of the Combustible Elements

Here we assume flight in the very rarefied layers of the atmosphere, when drawing oxygen from the air is difficult.

The elements of explosive materials for the rocket motion must have the following characteristics:

1. They must produce the maximum work per unit mass.
2. During combination, they must yield gases or volatile liquids which will revert to vapors during heating.
3. During combustion, they must develop the lowest possible temperature to prevent burning up or melting of the combustion chamber.

- 5 -

SECRET

SECRET

50X1-HUM

4. They must occupy a small volume; that is, have very great density.
5. They must be liquid and easily miscible. This makes the use of powders exceedingly difficult.
6. They may even be gaseous, but must have a high critical temperature and a low critical pressure so they may be satisfactorily used in compressed form. Compressed gases are generally disadvantageous because of their low temperature, since they absorb heat. Their use is accompanied by losses from evaporation and danger of explosion. Expensive unstable chemical products and products hard to obtain are also unsuitable.

Let us introduce an example. Hydrogen and oxygen satisfy all the conditions except those indicated in 4 and 5 above. Actually, liquid hydrogen is 14 times lighter than water (its density is 0.07) and therefore is unsatisfactory, since it occupies a large volume. The critical temperature of hydrogen is equal to -234 degrees, and oxygen to -119 degrees. Carbon alone is not suitable because of its solid state. Chromium, aluminum, potassium and other substances are unsuitable not only because of their solid state, but also because they form nonvolatile compounds with oxygen. Ozone is unsuitable, because it is expensive and chemically unstable. Its boiling point is -106 degrees centigrade. The majority of elements and compounds are unsuitable, because they release little energy per unit product under combination.

What substances are suitable?

1. Elements or compounds which are liquid at ordinary or not very low temperatures and which have a density close to the density of water. This means we may even permit compressed gases, but only those which have a low temperature.
 2. Those which produce the greatest work per unit of product obtained. Several slightly exothermic and in particular endothermic compounds. (The latter do not absorb, but release heat during decomposition and therefore are particularly satisfactory.)
 3. Inexpensive and chemically stable compounds.
 4. Those yielding volatile products during combustion: gases and vapors.
- The most vigorous component parts of explosive materials which yield volatile products are hydrogen and oxygen.

During the formation of steam, each kilogram produces 3,233 cal. The same combustion of light metals such as lithium, aluminum, magnesium, and also chromium and boron yields from 3,400 to 5,100 cal, i.e., substantially larger. However, these materials are unsuitable because the products are not volatile.

But, for the meantime, hydrogen and oxygen in their individual form are unsuitable. It would be better to replace them with weak compounds of other materials.

Thus, instead of hydrogen, we would have a hydrogen compound, and instead of oxygen an oxygen compound. Hydrocarbons are most suitable for combustion in oxygen, and hydrogen and carbon yield volatile products in combination with oxygen. In combination with oxygen, hydrogen gives greater energy than carbon per unit mass of product. Hydrogen gives from 3,233 (steam) to 3,833 (water), while carbon gives 2,136 cal. (All the preceding numbers are expressed in small calories for 1 mole of the material.) Therefore, the greater the percent of hydrogen, the greater the energy released during combustion.

- 6 -

SECRET

SECRET

50X1-HUM

These are saturated hydrocarbons. Of these, the most simple is methane CH_4 , or marsh gas. It contains a small percent of hydrogen (25%). But it should be taken into consideration that the majority of these compounds are exothermic, i.e., they release heat during their formation. When these compounds burn with oxygen, they must first decompose into H_2 and O_2 , thereby reversing their absorption of heat. Moreover, compressed methane has a low boiling temperature (-82 degrees centigrade) and is therefore unsatisfactory.

But let us calculate its energy of explosion. One part C requires two parts O_2 . Moreover, 94,000 cal are released per gram-molecule (mole). Four parts H_2 require two parts O_2 . For 36 g, 116,000 cal would be released. A total of 210,000 cal would be separated for 80 g. But the preliminary decomposition of CH_4 requires 185,000 cal for 16 g (mole). For 80 g, 181,500 cal remain. For one g of the products we obtain 2,394 cal.

Among the hydrocarbons there is one which contains a small percent of hydrogen (12.2%), but forms with the absorption of heat (endothermic compound). This is ethylene C_2H_4 . We find this more suitable. Actually, two parts C require four parts O . For 89 g to release 188,000 cal, four parts H_2 require two parts O_2 . For 36 g, 116,000 cal (steam) are released. This means that 124 g release 304,000 cal. But during decomposition C_2H_4 releases 15,000 cal of the heat absorbed earlier per 28 g. Thus, 319,400 cal are obtained in all. This is for 124 g. For one g of the products, we would obtain 2,576 cal. This is slightly greater than that obtained from methane. Ethylene is easily compressed, since its critical temperature is 10 degrees centigrade and the critical pressure is 52 atm. Ethylene is easily obtained from ethyl alcohol or ether by passing the latter through clay globules, heated to 300 - 400 degrees centigrade. The conclusion is that ethylene is more advantageous than marsh gas.

Now let us inspect benzene C_6H_6 . As the liquid is quite dense, it is most suitable for rockets. But it contains only 8% hydrogen. What is its energy per unit mass of products during its chemical combination with oxygen? During formation, it releases a total of only 102,000 cal per mole (a gram-molecule of 78 g). But, nevertheless, let us make our calculation. C_6 requires O_2 , and H_6 is necessary in O_3 . This means that 318 g of the products release 738,000 cal. Thence, calculating the absorption in the decomposition of C_6H_6 , we obtain 727,800 cal. This is for 318 g. For one g of the products we find 2,289 cal. This is slightly less than ethylene yields, but then we have a liquid at temperatures with very low vapor pressure. Acetylene is of the same percentage composition as gas and is unsatisfactory. Moreover, this exothermic compound releases a great deal more heat during its formation than benzene, approximately 18 times more. This means that it absorbs even more during combustion. Besides, the greater the carbon in the hydrocarbon, the higher the temperature of dissociation, and consequently the higher the temperature of combustion. Compressed hydrogen is the best of all; but obtaining and storing it are difficult, not to mention the huge volume it displaces.

We introduce data on the combustion heat of alcohols, ether, and turpentine.

Methyl Alcohol	CH_4O	2,123 cal
Ethyl Alcohol	C_2H_6	2,327 "
Ether	CH_4O_{16}	2,512 "
Turpentine	$\text{C}_{10}\text{H}_{16}$	2,527 "

- 7 -

SECRET

SECRET

50X1-HUM

Shown here are the calories released per unit of the products of combustion. It is obvious that these fuels cannot be disregarded.

In our calculations, we have assumed compressed oxygen. This is highly disadvantageous. Ozone is chemically unstable and is practically inadmissible. Therefore we turn to oxygen compounds.

Oxygen compounds of nitrogen are interesting. Let us find the one most suitable for us. The endothermic gaseous compound, nitrous oxide N_2O , is unsuitable because it contains a large percent of nitrogen. The same may be said for the endothermic compound nitric oxide NO . The third compound, nitrogen peroxide NO_2 , is a quite stable brown liquid. Its formation (synthesis) is accompanied by an insignificant release of heat. Chemically it is quite stable (up to 500 degrees centigrade) and very dense (1.49), which makes it very useful. It is a strong oxidizer, but covering tanks, pipes, cylinder's etc., with gold, platinum, iridium and other nonoxidizable substances or alloys will protect the machines from corrosion. The fifth sig compound, nitrogen anhydride N_2O_5 , contains slightly less nitrogen, but is unsatisfactory because of its chemical instability.

Let us examine NO_2 : this compound may be substituted for oxygen, but it is overloaded with nitrogen which decreases the speed of flight of the gaseous products of combustion, because their mass increases. We consider benzene; its gram-molecule is 78. We have seen that 78 g of this substance require 240 g of oxygen for full combustion. The weight of the products during combustion in pure oxygen is equal to 318 g. But instead of oxygen we have NO_2 . Here, 105 g of nitrogen are added. The products consequently will weigh 423 g. This quantity is greater by $423/318$ or 1.331 times. Because of the increased mass of the combustion products, their speed of flight will decrease 1.15 times, or about 87%. For example, instead of 6,000 m/sec, we will have 5,220 m/sec. The energy of explosion for one g of the products will be 1,721 cal.

It may be asked whether nitroglycerine, pyroxiline and others will not yield greater energy. As a matter of fact, they yield much less. The following table shows formation heats of the most powerful explosive substances for one g of the products in small calories.

Aluminum with ammonium nitrate	1,480
Powder and smokeless powder	from 720 to 960
Nitroglycerine powder	up to 1,195
Nitroglycerine	1,475
Dinitrobenzene with nitric acid	1,480
Trinitrophenol	750
Mercury fulminate	350

It is impossible to use these prepared explosive substances both because of the danger of an unexpected explosion of the entire mass and because of their low energy.

Resume

1. Hydrogen is unsuitable because of its low density and the difficulty of storing it in liquid form.
2. Compressed methane CH_4 yields 2,394 cal with liquid oxygen and is unsuitable because of its low boiling temperature.
3. Ethylene C_2H_4 yields 2,576 cal with O_2 . This mixture is more suitable, since ethylene has a critical temperature of 10 degrees centigrade.

- 8 -

SECRET

SECRET

50X1-HUM

4. Benzene C_6H_6 releases 2,289 cal with oxygen. The value of the energy here is small, but satisfactory in that benzene is liquid at normal temperatures. Even mixtures of liquid hydrocarbons with a high boiling point (kerosene and others) are suitable, the more so since they are inexpensive.

5. The use of liquid oxygen is slightly disadvantageous because of the difficulty of storing it.

6. Substituting nitric anhydride NO_2 for oxygen would be most suitable of all. This is a brown, chemically stable liquid denser than water. Upon mixing it with benzene, 1,721 cal are released per unit product.

These two liquids are the most suitable for rockets. But parts of the machine must be protected from the oxidizing effect of NO_2 . This energy (1,421 cal) is small, but it is larger than the energy of the very best powder and the most powerful explosive materials (nitroglycerine). Moreover, the latter are expensive and dangerous to use.

7. Alcohols and sulfuric ether are also useful. Let us further clarify the dependence between the combustion heat and the corresponding speed of the products of combustion under ideal conditions, i. e., in space and in very long tubes:

Heat, large calories	1,000	1,500	2,000	2,500	3,000
Speed of flow, m/sec	2,900	3,600	4,200	4,500	5,100

With ether, we obtain a speed of 5,630 m/sec. In this last case, during horizontal movement along rails or in the absence of gravity or resistance of the medium, we obtain the corresponding final speed of the chamber for various ratios of weight of fuel to weight of chamber with all its contents, except fuel and oxygen.

Ratio of weight of fuel to weight of formation	1	2	3	4	5	6	7	8
Maximum speed, m/sec	3,500	5,000	6,500	7,700	8,600	9,500	10,100	10,700
Ratio of weight of fuel to weight of formation		9		10				
Maximum speed, m/sec		11,100		11,300				

This means that with a ratio of 5:1 it may become a satellite of the earth and with a ratio of 10:1, a satellite of the sun.

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- 9 -

SECRET